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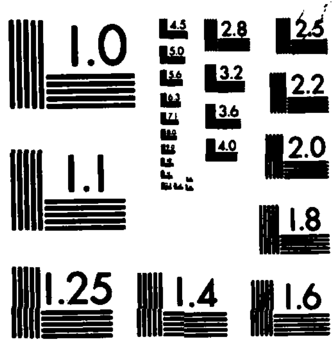

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Research and Development Technical Report
CECOM -82-C-J030-1

FIBER OPTIC EXPANDED BEAM CONNECTOR

JAMES F. RYLEY JR.
TRW INC.
Electronic Components Group
Research and Development Laboratories
Philadelphia, PA. 19108

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INTERIM REPORT FOR PERIOD

1 JAN. 1982 - 30 SEPT. 1982

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This interim technical report describes the first of two phases of development of a two channel, expanded beam, fiber optic connector. The connector has been designed with two Selfoc micro lenses per connector half providing the expanded beam nature. The preliminary development models (PEDM) resulting from this phase are explained in detail. The final models (phase II) will be based on these models with modifications mandated by test results and handling experience.

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FIBER OPTIC EXPANDED
BEAM CONNECTOR

CONTRACT NO. DAAB07-82-C-J030

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1 JAN. 1982 - 30 SEPTEMBER 1982

PREPARED FOR:

US ARMY CECOM
FORT MONMOUTH, NEW JERSEY 07703

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A

PREFACE

This interim technical report describes the development of a two channel, expanded beam, fiber optic connector as per contract #DAAB-07-82-C-J030 for the time period of 1 January '82 to 30 September '82. The funding for this contract is provided by the U.S. Army Communications - Electronics Command (CECOM). Managerial and technical guidance is provided by Vasilios Kalomiris at CECOM.

This work is being carried out at the TRW Electronics Components Group, Research and Development Laboratories in Philadelphia. The first phase of development represents the efforts of: Dr. Malcolm H. Hodge, Manager, Fiber Optics; Joseph F. Larkin, Senior Mechanical Engineer; and James F. Ryley, Jr., Project Leader.

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1.0 INTRODUCTION

The performance advantages of optical fiber communications in comparison to conventional metallic cables are well known. The use of optical fiber all but eliminates susceptibility to electromagnetic and radio frequency interference, as well as electromagnetic pulse. At the same time there is a significant reduction in weight and volume. These are primary factors in the decision to introduce fiber optics into the tactical environment. Tactical optical communications links require the use of cable assemblies to facilitate rapid deployment and mobility. The cable assemblies consist of 0.3 or 1 Km of ruggedized fiber optic cables terminated at each end by a connector.

The areas of fiber and cabling technology have made marked progress toward the development of suitable optical cables. Fibers with losses well below 1.0 dB/Km, at an operating wavelength of 1.3 μm, are commonplace. The connector area, however, is still developing. While various connector designs currently available meet most of the tactical requirements listed in Table 1 they do not meet them all. The exceptions are field cleanability and susceptibility to

TABLE 1

TACTICAL CONNECTOR REQUIREMENTS

. Hermaphrodicity	. Fungus Proof
. Ruggedized	. Salt Fog Proof
. Ease of Assembly and Repair	. Mud Proof
. Impact Resistance	. Submersible
. Vibration Resistance	. Field Cleanable
. Thermal Shock Resistance	. Flex Resistant
. Temperature Stability	. Tensile Load Resistant
. Moisture Proof	. Impervious to Repetitive Mating
. Sand Proof	. Low Insertion Loss (<2 dB)
. Dust Proof	. Reasonably Priced

dust which may damage the optical surface of the connector interface.

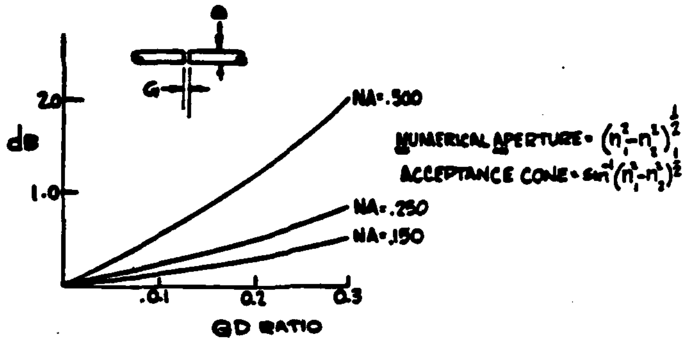
Recognizing the above problem, the Communications Systems Center (CENCOMS) of the US Army CECOM has funded a project for the development of a two fiber expanded beam connector. It is expected that the expanded beam design will offer improved reliability, facilitate field cleaning, and reduce the effects of particulates at the connector interface.

2.0 AREAS OF CONNECTOR DESIGN

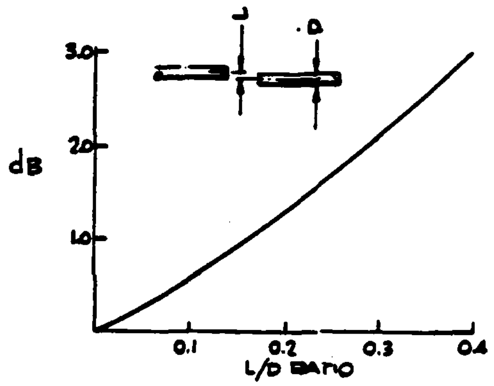
The development of an optical fiber connector can be divided into 3 major areas of concern: 1) optical alignment systems, 2) cable and fiber securing systems, and 3) connector shell design.

The positioning of the fibers, lenses, and windows are all part of the total optical alignment system and, to a large extent, determine the quality of the connection. Fiber alignment must be repeatably accurate yet accomplished with as much facility as possible during connectorization of cables. The accuracy necessary in a direct fiber-to-fiber (butt) connection is demonstrated in Figures 2.1 to 2.3. The tolerances imposed on lateral offset and end gap misalignments can be relaxed by using an expanded beam technique. This, however, tightens angular sensitivity. These techniques will be explained in detail in the following section. In designs utilizing windows and lenses, additional considerations should be made. The surfaces of both will create Fresnel reflections causing unnecessary signal loss if counteracting measures are not taken. Proper anti-reflection coating or use of index matching techniques can all but eliminate this problem. Windows should be easily replaceable in that they could be subject to abrasion and breakage.

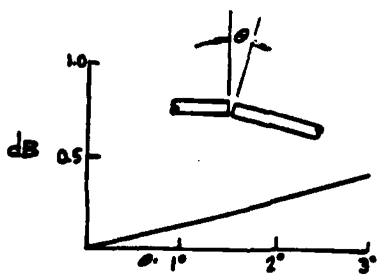
Both the fiber itself and the cabling must be anchored within the connector body to give the cable assembly (cable and connector) the necessary tensile strength. Securing the cable against tensile loads is primarily a case of capturing the cable strength members in a manner commensurate with the expected service environment The actual method used is dependent not only on the load requirement but also on the design of the cable(s) to be accommodated. Depending on the cable, the strength members could range from a polymer aramid material such as Kevlar, to a steel, or to a combination of these materials. The fiber



GAP LOSS



LATERAL MISALIGNMENT LOSS



ANGULAR LOSS

Figures 2.1 - 2.3: Fiber To Fiber, Butt Connection Misalignments

or buffered fiber should also be fixed to preclude even the slightest movement. A number of epoxy potting and clamping methods have been devised. Care must be taken to avoid the introduction of microbend losses when selecting a method.

The connector shell should be designed to serve a number of functions. Paramount among these are: the stable location of the interior components, protection of these components from hostile environments, provision of required coupling characteristics (hermaphrodicity, free rotating coupling ring, etc.), and cable strain relief. The inclusion of all the necessary attributes represents an extensive design effort on the shell alone.

2.1 THE EXPANDED BEAM CONCEPT

An expanded beam design, as its name implies, is one in which the diverging beam emergent from an optical fiber is expanded and collimated, by a lens, before traversing the interface between two connector halves (Figure 2.1.1). This action affords a number of important benefits. By expanding the beam beyond the

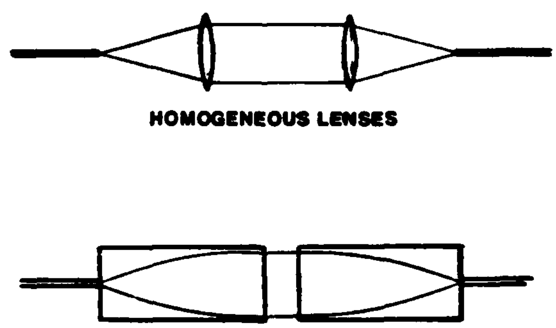
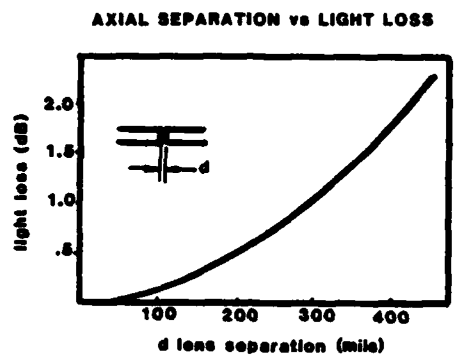


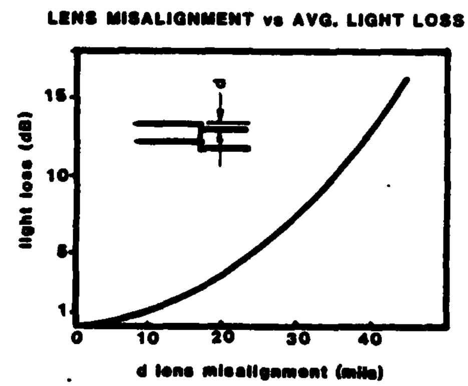
Figure 2.1.1 Beam Collimation By Lens

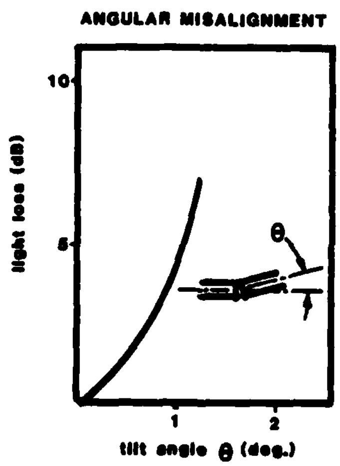
size of the fiber core the connection becomes less susceptible to dust and dirt particles that could normally block large portions, if not all, of the signal. The received beam is reduced by only that percentage which the particle's cross sectional area represents of the beam's cross sectional area. Hence the larger

the expansion the lower the susceptibility. The beam's collimation is of great importance. A well collimated beam can travel considerable distances without expanding beyond the receiving elements aperture. This allows the placement of windows at the connector input/output faces without adversely affecting transmission. The beam passes through the windows and any gap between them without further expansion as would be experienced by the unaltered beam from a fiber. The ability to seal the connector face with a window rather than some body including the fiber face in its outer surface (pot and polish type connector, etc.) is particularly attractive in a tactical environment. The window serves as a transmission surface that is field cleanable by either spraying or wiping or a combination of the two. As with particulates this design type is much less sensitive to signal degradation by abrasion (from wiping) than an exposed fiber design. The window also protects the optical components inside from any sand-blasting action it is likely to incur. Once the window has sustained appreciable damage it is more readily replaced than the fiber itself in a sealed connector with proper design.

As mentioned in section 2.0, the use of a lens has one notable draw back, that of sensitivity to angular misalignment. Inspection of Figures 2.1.2 to 2.1.4 will reveal that, although the sensitivity to lateral and gap misalignments has been markedly reduced, the sensitivity with respect to angular misalignment of the lenses themselves is increased in comparison to fiber-fiber butt connections (Figures 2.1 to 2.3). Thus, the lens mounting technique must include a high level of angular accuracy.







Figures 2.1.2 - 2.1.4: Lensed Connection Misalignments

3.0 TECHNICAL DISCUSSION

This contract calls for the two phase development of a two channel, expanded beam, fiber optic connector. Phase I, including the design, production, and testing of a Preliminary Exploratory Development Model (PEDM), has progressed to mid test sequence at the time of this writing. Four models (2 plugs and 2 bulkhead receptacles) are under testing and will be delivered to Ft. Monmouth upon testing completion. Phase II involves the production and testing of 12 final models (FEDM) based on the results of a critical design review of the PEDMs. The optical system has been designed to repeatedly provide an insertion loss, per channel, of less than 2.0 dB with a crosstalk level of less than -60 dB with respect to the exciting signal. The mechanical systems have been designed to provide the necessary accuracy for optical alignment and to maintain this alignment under the environments prescribed in the contract Technical Requirements section (Appendix A). The assembly tooling and procedure will also be discussed in detail.

3.1 OPTICAL DESIGN

3.1.1 Selfoc Lens Technology

The heart of the optical design is the Selfoc[(R)] microlens. The Selfoc lens is a right circular cylinder having a quadratic refractive index gradient in the radial direction similar to that of a graded index fiber. The cylindrical shape makes this type of lens easier to mount than the more traditional homogeneous spherical lens. The index gradient is produced by an ion exchange technique. Two ion exchange methods are used. The first uses a molten salt bath. Here the salt, KNO_3, is maintained at approximately 500°C which is near the softening

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[(R)] Selfoc is a trademark of the Nippon Sheet Glass Co.

point of the borosilicate glass used as a substrate. The second technique is a double crucible method in which the core and cladding glasses are heated to $\sim 900^{\circ}C$ and a continuous fiber drawn through a coaxial nozzle at the center of the crucibles where the ion exchange occurs. Figure 3.1.1 illustrates the mechanism of the ion-exchange procedure. The glass compositions at the center

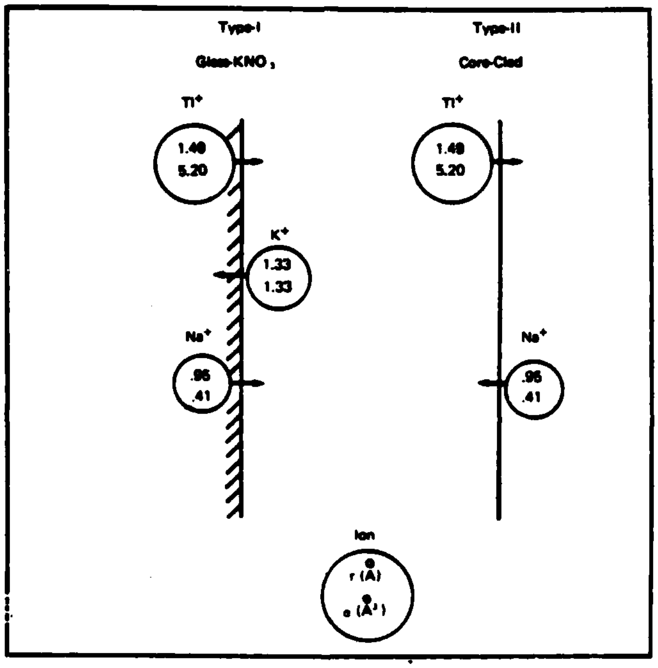

Figure 3.1.1 Mechanism of Ion-Exchange

and the periphery are totally different at the conclusion of these procedures. The result is a parabolic optical index cross-section. These lenses are available in a number of types differing primarily in numerical aperature (N.A.), length and diameter. Numerical aperture and diameter are chosen to accommodate the fiber to be used. The lens' N.A. should be equal to, if not greater than that of the fiber to avoid excess loss. The importance of length selection can be seen by inspecting the equations governing a ray's trajectory through the lens. The refractive index at any point r measured from the optic axis is given by:

$$N(r) = N_o \left(1 - \frac{A}{2} r^2\right)$$

where N_o = refractive index on optic axis

A = refractive index gradient constant

Using this equation the following ray matrix results assuming the lens is immersed in air:

$$\begin{bmatrix} r_2 \\ \dot{r}_2 \end{bmatrix} = \begin{bmatrix} \cos\sqrt{A}\,Z & \frac{1}{N_o\sqrt{A}} \sin\sqrt{A}Z \\ -N_o\sqrt{A}\sin\sqrt{A}\,Z & \cos\sqrt{A}\,Z \end{bmatrix} \cdot \begin{bmatrix} r_1 \\ \dot{r}_1 \end{bmatrix}$$ [1]

where:

r_1 = distance of incident point from the optic axis.

$\dot{r}_1$ = incident angle (radians)

r_2 = distance of emitting point from optic axis.

$\dot{r}_2$ = emitting angle (radians)

Z = lens length (mm)

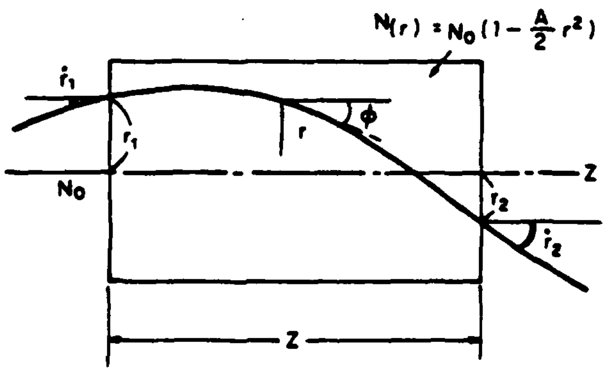

Figure 3.1.2 Focus Of A Ray Passing Through A Selfoc Lens

From this we obtain the relationship between the input and output coordinates of a ray:

$$r_2 = r_1 \cos\sqrt{A}\,Z + \frac{\dot{r}_1}{N_o\sqrt{A}} \sin\sqrt{A}\,Z \qquad (2)$$

$$\dot{r}_2 = -r_1 N_o \sqrt{A} \sin\sqrt{A}\,Z + \dot{r}_1 \cos\sqrt{A}\,Z . \qquad (3)$$

[1] Technical Data Sheet, Selfoc Fiber Optic Devices, Nippon Sheet Glass Co., Ltd.,1981.

Using Snell's law and assuming small angles we can write:

$$r_2 = r_{2i} \qquad r_1 = r_{1i} \tag{4}$$

and

$$\dot{r}_2 = N_o \, \dot{r}_{2i} \qquad \dot{r}_1 = N_o \, \dot{r}_{1i} \tag{5}$$

where:

r_{2i} = distance of output point from optic axis.

$\dot{r}_{2i}$ = output angle (<u>inside</u> exit face)

r_{1i} = distance of input point from optic axis

$\dot{r}_{1i}$ = input angle (<u>inside</u> input face).

Substituting into the above equations:

$$r_{2i} = r_{1i} \operatorname{Cos} \sqrt{A}\, Z + \frac{\dot{r}_{1i}}{\sqrt{A}} \operatorname{Sin} \sqrt{A}\, Z \tag{6}$$

$$\dot{r}_{2i} = -r_{1i} \sqrt{A} \operatorname{Sin} \sqrt{A}\, Z + \dot{r}_{1i} \operatorname{Cos} \sqrt{A}\, Z . \tag{7}$$

With these equations, mediums other than air at the lens faces may be investigated. The point of interest is the focal point of the lens i.e. the fiber face must be located at this point to give the desired collimated output beam. Applying Snell's law to the geometry of Figure 3.1.3, and again assuming small angles, we can express the relationship for focal point location in an arbitrary medium of index

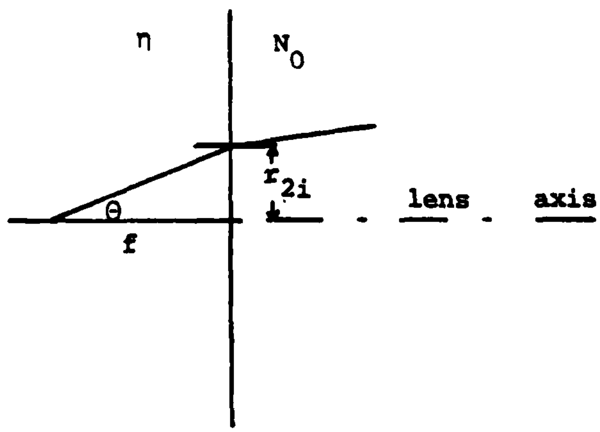

Figure 3.1.3 Focal Point Geometry

η (N_o has been used for the core index regardless of location since the index variation from axis to beam edge is on the order of 0.001) as:

$$f = \frac{r_{2i}}{\tan\theta} \qquad (8)$$

where:

$$N_o \; \dot{r}_{2i} = \eta\theta \text{ (Snell's law for small angles)}$$

$$\theta = \frac{N_o}{\eta} (-r_{1i} \sqrt{A}) \sin \sqrt{A}\, Z \text{ (using eq. (7)).}$$

Then using eq. (6),

$$|f| = \frac{\eta}{N_o \; \sqrt{A} \tan \sqrt{A}\, Z}. \qquad (9)$$

To achieve a focal point at the lens face ($f = 0$) we must have $\tan \sqrt{A}\, Z = \infty$ or $\sqrt{A}\, Z = \pi/2$ radians. If a length shorter than this Z is used the focal point will be outside the lens by some distance. The location of the focal point is also wavelength dependent. Both $\sqrt{A}$ and N_o vary with wavelength as shown in Table 3.1.1.

Wavelength (nm)	Length (P)	$\sqrt{A}$ (mm^{-1})	N_o
632.8	0.237	0.337	1.610
830.0	0.230	0.328	1.602
1300.0	0.223	0.318	1.595
1560.0	0.221	0.315	1.593

Table 3.1.1 Wavelength Dependency Of $\sqrt{A}$ and η_o For The Selfoc Lens (Nippon Sheet Glass technical bulletin on Selfoc Lens)

Therefore, the operating wavelength must be taken into account in system design.

3.1.2 Fiber Alignment Subassembly

The SLW-1.8 mm diameter, 0.23 pitch lens has been chosen for use in this connector. As mentioned previously, such a length will result in a focal point removed from the lens face. This choice stems from the selection of the fiber alignment system to be used. The fibers will be positioned at the focal point by means of one half of a TRW proprietary alignment guide. The full guide (Figure 3.1.4) is designed to bring fibers entering from opposite ends into axial alignment by disposing (through the bends) the fibers to travel along the upper cusp. One half of this guide will, then, bring the fiber axis into

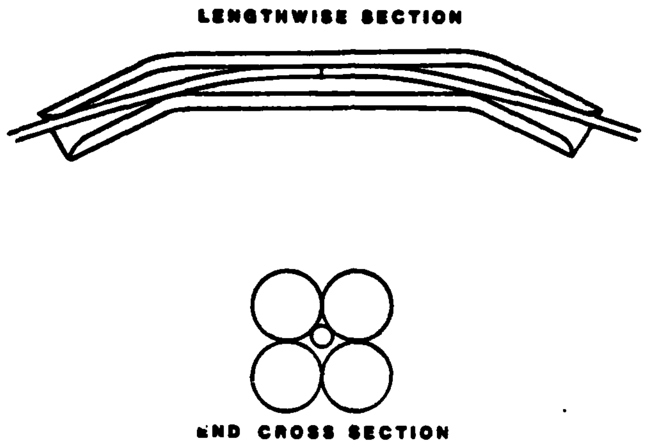

Figure 3.1.4 TRW Fiber Alignment Guide

normal orientation with any flat surface placed against it. The half guide is secured to the slug end plate (BK 7 glass, $\eta = 1.52$) which is in turn bonded to the Selfoc lens as shown in Figure 3.1.5. It is the use of this endplate that

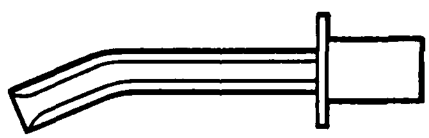

Figure 3.1.5 "Half" TRW Alignment Guide Joined To Selfoc Lens

necessitates the use of a lens with the focal point outside its end face. The endplate serves two functions: 1) active alignment of the fiber guide without the endplate would move the fiber face across the lens face in direct contact possibly scratching the lens - the endplate eliminates this, and 2) during the active positioning process the bonding material is still fluid and would capillary flow into an unsealed alignment guide - this is also eliminated by the

use of the endplate. The thickness of the endplate must correspond to the focal length f. Using the equation developed earlier:

$$f = \frac{1.52}{\eta_o \sqrt{A} \tan \sqrt{A}\, Z}$$

we obtain the following focal lengths

at	6328Å	:	f	= 9.3 mil
"	8300Å	:	f	= 14.2 mil
"	13000Å	:	f	= 20.0 mil

The PEDMs have been configured with endplates of 14 mils for 830 nm operation. Final models (FEDM) will use 20.0 mil plates for 1300 nm operation. The preliminary models have been designed at 830 nm solely to expedite progress as our current test facilities are calibrated at this wavelength. Recalibration at 1300 nm will be completed for Phase II. The step by step positioning of the fiber alignment guide is detailed in section 3.3. Because of the prior positioning of the guide, a fiber from the cable to be terminated can be inserted into the flared end of the guide and advanced until it butts against the glass plate and it will be accurately located with respect to the lens focal point. The advantages of this arrangement are both in simplicity of field assembly and the elimination of any field splicing necessary when the lenses are "pigtailed".

The complete fiber alignment subassembly is shown in Figure 3.1.6. A glass support tube has been added around the alignment guide at the guide/end plate interface for support. Each of these assemblies is then shrouded in a thermoplastic polyester slug (Figure 3.1.7). The slugs act as both fiber insertion sleeves (guaranteeing that the fiber enters the alignment guide flare) and as fiber guide protection. As can be seen from Figure 3.1.6 this subassembly is bonded together using a number of different epoxies. Each different epoxy was

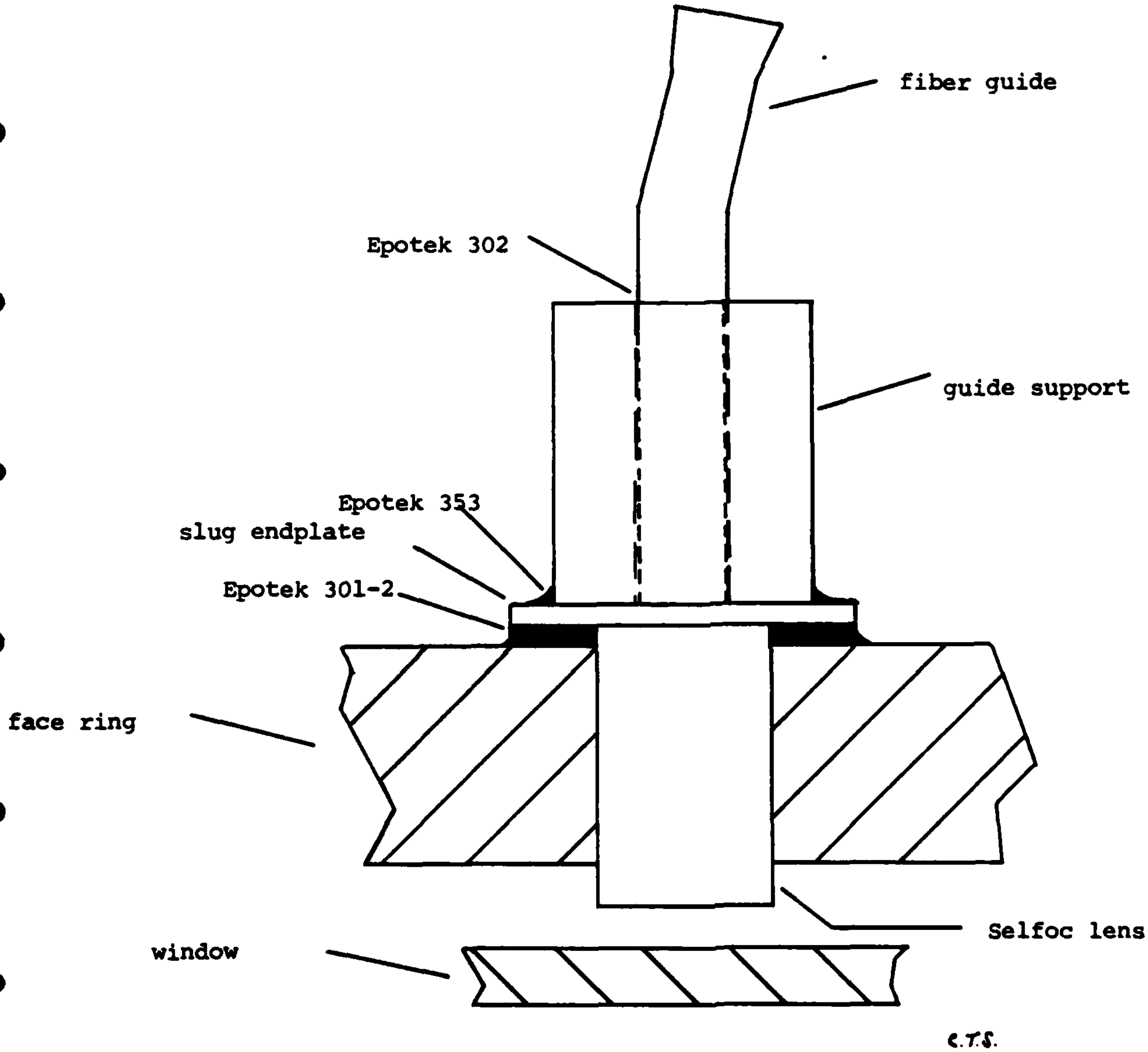

Figure 3.1.6: Fiber alignment subassembly.

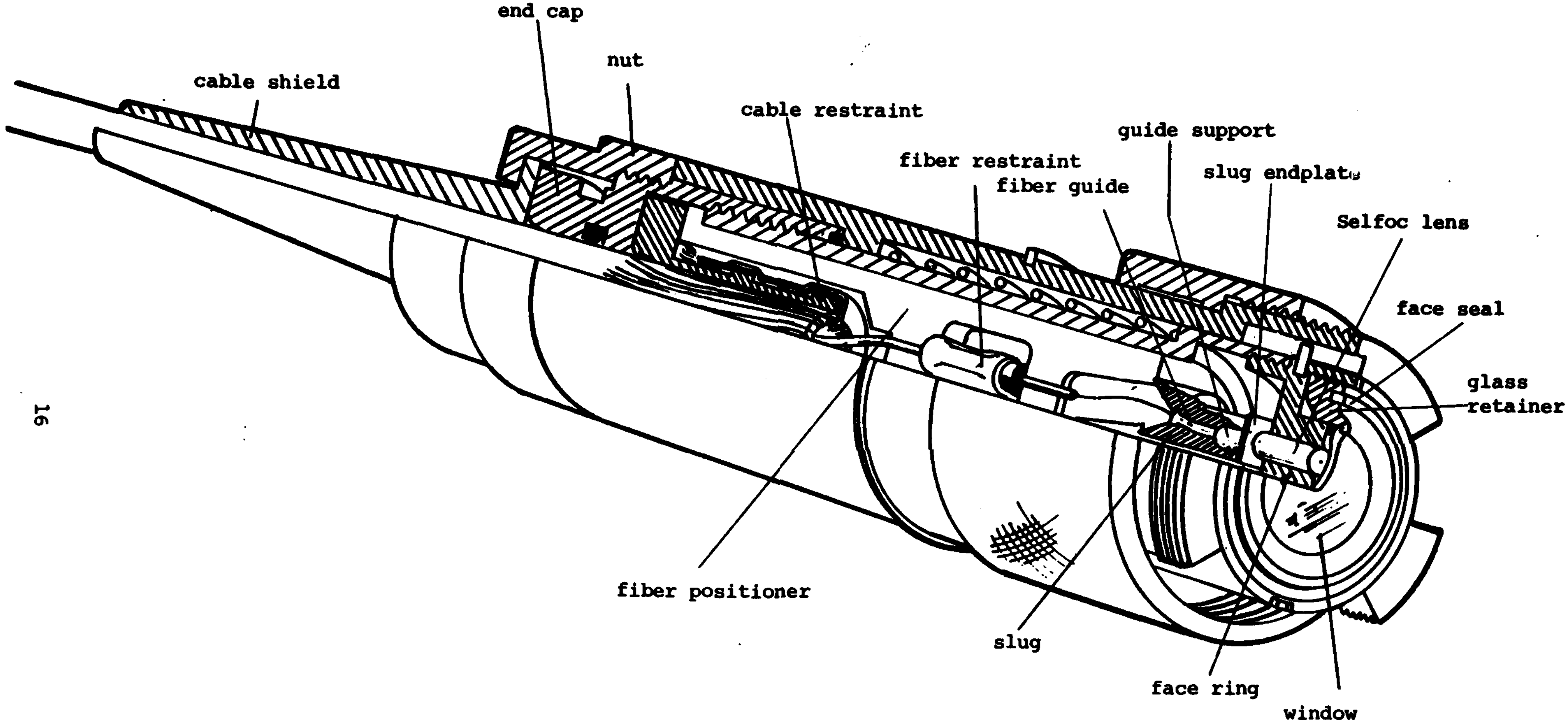

Figure 3.1.7: Connector cutaway view.

TRW

selected based on advantages it offered over the others in that particular location. Basic considerations at the slug end plate/lens interface were optical transmission, operating temperature range, strength, and moisture resistance of the compounds available. Epotek 301-2 appeared to be superior with an operating range of -45°C to +200°C, a transmission in the infra-red of 98-99% (3000Å to 2.5 microns for a .001" sample), a lap shear strength of 2000 psi (Al to Al), and moisture resistance meeting Mil. Std. 750 Test 1021.1. The adhesive used at the slug end plate/guide support bond line has no optical requirement. Here we looked mainly for strength, cure time, and temperature performance. Epotek 353ND was chosen for this. The final bondline is that between the guide support and the fiber guide. Again there are no optical requirements here. Rather, an adhesive with a high viscosity and short cure time was needed to allow the epoxy to set before it was able to flow from the top of the support to the bottom. Epotek 302 has a viscosity of about 5000 cps and a pot life of 5-10 minutes. The lens are also mounted (in the face ring) using 301-2.

3.1.3 Antireflection Coatings

With a multi-layered optical system such as we have here it is important to consider the effects of Fresnel reflections, and reflections due to abrupt changes in index of refraction. The coefficient for such a reflection, assuming normal incidence, can be written as:

$$R = \frac{(\eta - \eta_1)^2}{(\eta + \eta_1)^2}$$

where

η = index of medium light is reflected from

η_1 = index of medium light is propogating in.

The reflected power would be R times the incident power. The surfaces to be considered in this design are the fiber face, both slug endplate surfaces, both lens surfaces, and both window surfaces (Figure 3.1.5). The two slug endplate surfaces and adjacent lens surface are well index matched ($\eta \simeq \eta_1$) by the epoxy. The fiber face is matched by the silicone oil filling the alignment guide. The two window surfaces and remaining lens surface, however, are not index matched. The changeability of the window prohibits the use of an index matching medium in the air space between the window and lenses. Instead, an antireflective coating has been applied to these surfaces. The idea here is to produce destructive interference between two reflected beams. This is achieved by configuring the window and coating such that the reflections are at interfaces going from less dense to more dense materials and having a π phase shift resulting from propagation length in the second medium (Figure 3.1.8). The layer thickness must be chosen such that

$$\frac{4\pi\ \eta_2 d}{\lambda_o} = \pi \quad \text{or} \quad d = \frac{\lambda_2}{4}$$

(at $\eta_2 = 1.38$, $\lambda_o = 820$: $d \simeq 149$ nm)

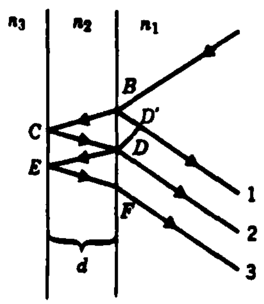

Figure 3.1.8 Multi-Layer Reflection Geometry

where λ_o is the wavelength in air. The coating material is then chosen such that $\eta_1 < \eta_2 < \eta_3$. In this way the electric field amplitudes of the reflected beams 1 and 2 will be π out of phase with each other as a beam experiencing a near normal incidence reflection from a surface of higher index than the propagation medium experiences a 180° phase shift. Calculations show that these conditions, assuming a quarter wave coating thickness, reduce to

$$\rho_{12} \simeq \rho_{13}$$

where

$$\rho_{12} = \frac{\eta_1 - \eta_2}{\eta_1 + \eta_2} \quad \text{and} \quad \rho_{23} = \frac{\eta_2 - \eta_3}{\eta_2 + \eta_3}$$

(ρ_{12} and ρ_{13} are amplitude reflection coefficients) for near zero reflection. Substituting further we have the basic condition

$$\eta_2 = \sqrt{\eta_1 \cdot \eta_3} \ .$$

Assuming $\eta_1 = 1.0$ (air) this condition implies that the ideal coating index for the lens ($\eta = 1.6$) and the window ($\eta = 1.52$) are 1.26 and 1.23, respectively. MgF_2 (η=1.38) is closest in index to this of materials with good environmental properties. As indicated in Figure 3.1.9, the coating reduces reflections in the 830 nm region to less than 2%. Reflections without this coating would exceed 5% at each interface. The coatings have been deposited at high temperature to insure hardness. The resulting temperature is over 200°C.

3.2 MECHANICAL DESIGN

3.2.1 Fiber Positioning and Securing

The selfoc lenses are bonded into the face ring as indicated in Figure 3.1.7. The alignment subassemblies are then bonded to the lens/face ring combination. It is necessary then to provide some means of insuring fiber insertion into this alignment subassembly on cabling the connector. This function, among others,

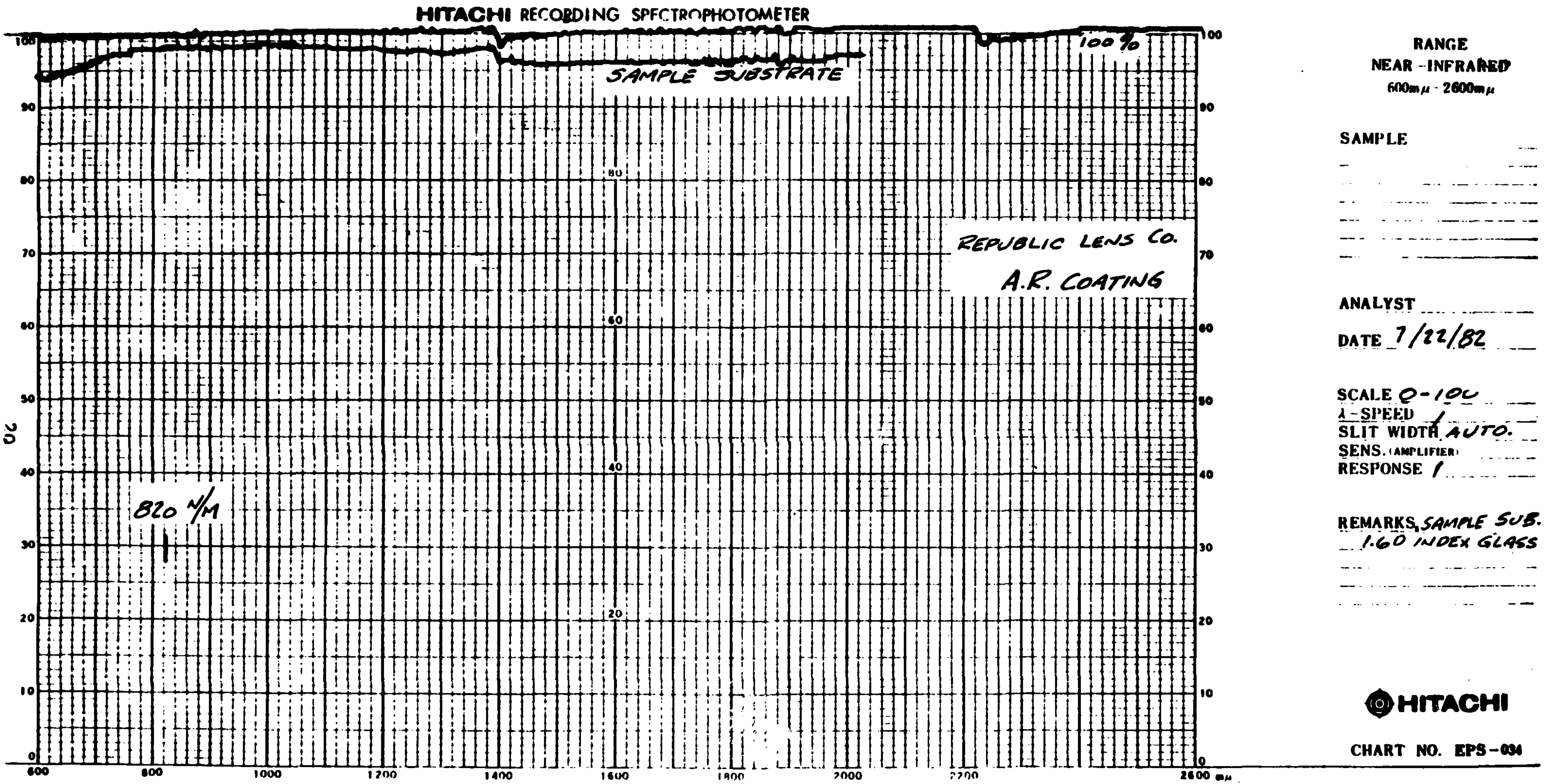

Figure 3.1.9: Transmission curve for A.R. coatings.

is provided by the fiber positioner (Figure 3.2.1) and positioner housing.

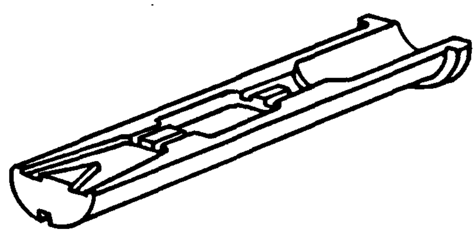

Figure 3.2.1 Fiber Positioner

The face ring/fiber alignment subassembly screws onto the front of the positioner housing. These pieces are tightened until opposing scribe marks are aligned. The fiber positioner, with the fibers secured by crimps held in the cavity approximately mid-way in the piece, is then slid into the positioner housing from the rear. To accomplish this, slots in the positioner must be lined up with pins in the housing. These pins and the scribe marks insure polarization between the positioner and face ring. The fiber crimp is composed of one rubber and one aluminum ferrule per channel. The rubber ferrule is fed over the fiber's protective jacket and the aluminum ferrule is then slid over that and crimped. This combination gives good retention with losses less than 0.1 dB (typically 0.0).

3.2.2 Cable Securing

The cable must also be secured in such a fashion that tensile loads or flexural loads do not affect the optical performance of the connector. This is accomplished by capturing the cable strength member (Kevlar) in another crimped ferrule type arrangement. Kevlar is an aramid fiber, with 3 to 4 times the strength to weight ratio of steel, commonly used in optical cables. The crimp

configuration in this case is composed of a double ridged, stainless steel inner ferrule and brass outer ferrule. The stainless steel ferrule is slid over the cable, the Kevlar folded back over this ferrule, and the brass ferrule then slid over this composite and crimped (Figure 3.1.7). This crimp is seated in the rear of the fiber positioner. The double key at the rear of the positioner keeps the crimp and cable from spinning under torsional loads. Once in the connector shell the crimp is held firmly in place by the end cap. Cable strain relief is provided by a molded rubber shield attached with the end nut.

3.2.3 Connector Shell

The connector shell must provide for stable location of the interior components as well as the protection of these components from adverse environments. In this particular case the shell must also provide for hermaphrodicity.

As can be seen from the cutaway view of the connector, hermaphrodicity is accomplished by the castellation of the coupling threads. These castellations are further arranged to prohibit mating in any but the intended orientation. Once the castellations of two halves to be mated have been interdigitated they are secured by either or both coupling rings. These rings are free spinning as required by the contract.

The shell itself, as well as the coupling ring and interior metal parts, is made of stainless steel. The inner diameters of the shell are such as to allow the interior assembly to retreat back into the shell upon mating. The length of this withdrawal is restricted by a dowel pin (in face ring) - slot (in shell) arrangement. As the two connector halves are brought together the pin slides back along the slot until bottoming. Further tightening provides ample forward pressure. The coil spring repositions the interior assembly on decoupling. Mating accuracy is unaffected by the play allowed by this telescoping movement. The connector shell does not serve as the mating surface in this

design. Rather, the foremost edge of the face ring serves as this surface. The importance of this feature is dealt with in section 3.3.

3.2.4 Connector Sealing

The humidity, immersion, dust, mud, and temperature environments imposed by the contract (Appendix A) dictate that this connector be a sealed design. Inspection of Figure 3.1.7 shows 5 seal locations. Four of these are involved in the sealing of the connector interior. The fifth, located on the glass retainer, seals the small cavity created between the windows of two mated halves. This prevents the intrusion of any foreign materials into this space during operation. The locations and purposes of the first four seals are, from left to right, as follows: 1) an o-ring rod seal in the end cap to seal the cable feed through, 2) an o-ring compression seal between the shell and end cap to complete the interior seal from the rear, 3) the bonded interface between the face ring and positioner housing to complete the interior seal from the front, and 4) an o-ring compression seal under the window to keep moisture from the lens area.

3.2.5 Plug Vs. Bulkhead Versions

The bulkhead and plug versions differ only in the threading of the mid-section of the bulkhead shell to accept a jam-nut for panel mounting. The threaded portion has been configured for D-hole type mounting as required.

3.3 CONNECTOR ASSEMBLY

3.3.1 Pre-delivery Assembly

The fiber alignment sub-assembly/face ring structure is completely assembled prior to delivery. The sub-assembly itself needs no further explanation. The positioning of the sub-assembly on the face ring, however, is critical and

warrants further discussion.

In view of the sensitivity of lensed connections to angular offsets (section 2.1), the connector has been designed such that the mating surfaces are the foremost annular surfaces of the face rings i.e. the same bodies holding the lenses. This minimizes any angularity between opposing lenses in the mated condition. Recognizing this, it is easy to see that a beam exiting a connector half should be parallel to the face ring axis. In this way the beams received by mating halves will always focus at the same point regardless of any lateral offset caused by mechanical tolerance build ups. The quickest and surest way to find this focal point is to simulate the optical path in reverse, i.e. to inject a collimated beam into the output side of the lens and manipulate a receiving fiber at the other face until the focal point is located. A HeNe laser is being used as the source of a collimated beam. By inputting the laser's parallel beam to find the focal point we insure that the output from a fiber located at this point and carrying the same wavelength will be collimated. Furthermore, if the laser beam is parallel to the face ring axis the output from the fiber/lens compound will be also. The alignment fixture has been designed to insure this parallelism to better than 0.1°. A schematic of this fixture is presented as Figure 3.3.1. The laser has been fitted with a beam expander to allow simultaneous, homogeneous illumination of both lenses. The expander also improves the already 1.2 mr divergence of the laser. The laser is mounted to an optical rail by means of a precision V-block mount. The expanded beam is fed into a tube having a pair of precision apertures at each end. The tube length ($\sim$17") has been chosen to provide the beam/face ring axis parallelism desired. The 30 mil aperture diameter selected will provide the lenses with the same numerical aperture as the intended fibers ($\sim$0.2) as can be seen from the following calculation at 820 nm.

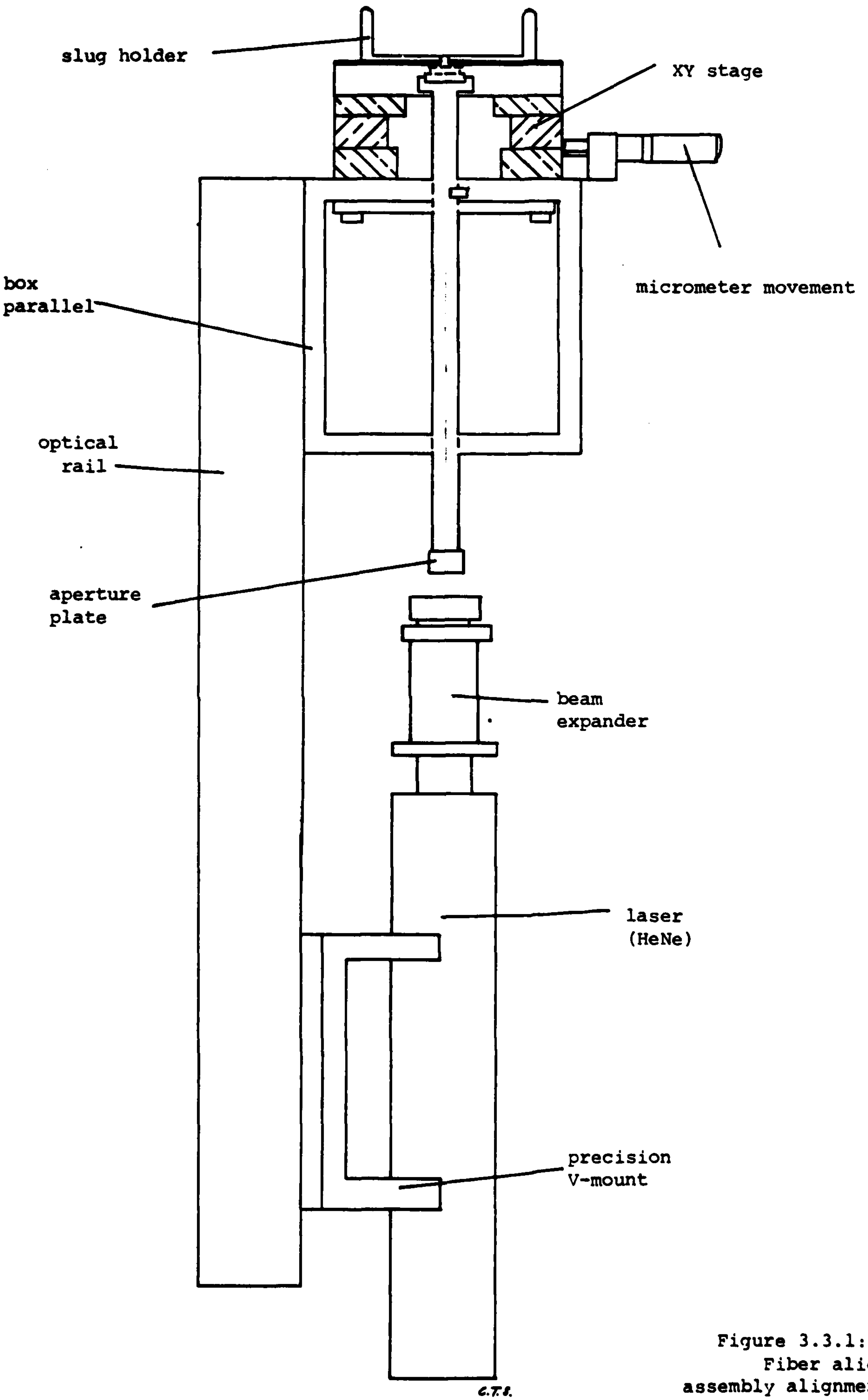

Figure 3.3.1:
Fiber alignment sub-
assembly alignment fixture.

The output radius is given by:

$$r_o = r_i \cos(\sqrt{A}\,L) + (\dot{r}_i/\sqrt{A}) \sin(\sqrt{A}\,L) \quad \text{(from eq. 6)}$$

where:

$$\sqrt{A} = .328\ \text{mm}^{-1}$$

$$L = 4.41\ \text{mm}$$

and i designates input values just inside the lens face.

r_i and $\dot{r}_i$ are determined by considering the fiber's properties and those of the slug end plate. The fiber has a core diameter of 50µm and an N.A. of 0.19. A ray leaving the edge of the fiber at maximum angle will enter the lens at an angle of 7.2° and at a radial distance of 0.072 MM. This is assuming the end plate is BK 7 having an index of 1.52. This gives $R_o = (.072) \cos(1.446) + \frac{1}{.328}$ $(.124\ \text{rad}) \sin(1.446)$ or $R_o = .384$ mm = 15 mils. The tube is mounted through a box parallel which, in turn, is mounted to the optical rail. The top of the tube is fitted with a holder mimicking the face of a connector. It is on this holder that the face ring/glass retainer sub-assembly is placed for alignment. In this way alignment is done with the optical portions completely assembled and in the same configuration they will be in when mated to another connector half. Thus, tolerances in window mounting and lens mounting are accounted for automatically. The fiber alignment sub-assemblies (discussed in the previous section) are then manipulated by an X-Y translation stage fitted with holders and mounted to the top surface of the box parallel. During this operation, a test fiber is inserted and the maximum output reading sought. The fact that the HeNe emits at 632.8 nm instead of the 830 nm operating wavelength has no effect on the location of the focal axis as long as the diverging nature of the 632.8 nm beam at this point is taken into account since the focal point of all wavelengths will fall on the same axis. The impact of this on our results is discussed in section 4.3.

3.3.2 Cable Connectorization

The procedure for applying the connector to the ITT, two fiber, cable used on this program is as follows:

1. Slide end cap, fiber positioner, and double ridged stainless cable crimp inner ferrule over cable (in that order).
2. Strip 4 inches of the black cable outer jacket from cable (Ideal cable stripper or other appropriate tool).
3. With the stainless steel inner ferrule positioned such that the cable jacket is flush with its front edge, fold the Kevlar back over the ferrule.
4. Slide the brass outer ferrule over this and crimp into place. (Palladin crimp tool-provided).
5. Trim excess Kevlar as close to brass ferrule as possible.
6. Lay cable crimp into the fiber positioner and run protected fibers through appropriate channels.
7. Mark point at which fibers enter fiber crimp cavity on both fibers. Remove from positioner.
8. Apply fiber crimps to both fibers by first sliding rubber inner ferrule to within ∿1/8 inch of this mark then sliding the aluminum ferrule over the rubber ferrule until its leading edge passes the rubber ferrule's leading edge and comes to the mark. Crimp in place (Palladin tool-supplied). Repeat for second channel.

   (Note: Upon replacing in positioner the rear edge of both ferrules should lay against the rear wall of the crimp cavity).
9. Replace cable and crimps into positioner. Mark point at which fibers exit the final set of channels (just forward of crimp cavity). Remove from positioner.
10. Strip Hytrel (protective) coating back to this mark using 10 mil NoNik strippers (provided) (about one inch at a time works best).

11. Protect bare fibers by immersing in Trimethylchlorosilane for 2 minutes.

12. Scribe fibers 1.765" ± 0.003" from rear face of aluminum ferrule.

    Note: This face, always being against the rear face of the ferrule cavity, is used as the scribe length index surface.

13. Replace cable and crimps into fiber positioner and bond fiber crimps (aluminum) in place with a 5 minute type epoxy. (This will not be necessary on FEDM versions).

14. Close fiber positioner with other half positioner.

15. Load spring into connector shell from front.

16. Slide positioner housing/face assembly (pre-assembled) into shell being sure dowel pin enters slot in shell.

17. Place o-ring over rear of positioner housing and slide o-ring down to shoulder in shell.

18. Insert fiber positioner/cable assembly into rear of positioner housing again taking care to align dowel pins and slots.

    Note: Be cautious not to damage protruding fibers.

19. Slide positioner nut up and screw tightly into place. The interior parts are now locked in place.

20. Slide end cap up and screw into place.

An assembly machine, automatically insuring distances between crimps and scribe lengths, will be delivered with the FEDMs. This machine will have all crimping and scribing tools mounted to it.

4.0 CONNECTOR TESTING

A portion of the environmental testing to be undergone by the PEDMs was completed during the period covered by this report. Test conditions, test instrumentation, and the results of these tests (shock, vibration, and high temperature) are presented in this section.

4.1 Baseline Coupling Loss and Crosstalk

Coupling loss shall be defined as the difference between the signal strength of the unbroken cable and the signal strength for the same cable broken and re-fastened using the expanded beam connector.

The signal was injected using two Laser Diode Laboratories IRE-160 FB light emitting diodes (LED). The diodes are pigtailed with a 125 μm/50 μm graded index fiber. Driven at 100 mA approximately 15 dB (μw) can be injected into each channel.

The LED drive current was monitored continuously throughout the test using a Fluke 8010A digital multimeter. We have found that, with the current kept in the 100 $\pm$ 2 mA range, the IRE-160 has an extremely stable output ($\pm$0.1 dB (μw)). Emission of this LED is peaked 820 nm (spectral width is 40 nm). The difference in transmission between this wavelength and 850 nm is insignificant. Baseline coupling loss and crosstalk levels (paragraph 3.3.1 of the contract Technical Requirements) shall be established using the following procedure:

1) measure signal transmitted by 30 feet of unbroken cable (both channels)
2) break cable at midpoint and install the connector pair to be tested (section 3A).
3) measure the transmission of both channels.
4) with LED #1 off measure both near end and far end crosstalk present in channel 1. Repeat for channel 2.

5) remove the connector halves from the cable, re-repare the fiber ends, and reinsert the connector. Repeat steps 3 and 4. (Note: be sure to keep channel identification constant)

6) Repeat step 5 eight times for a total of 10 measurements per configuration (a total of 50 measurements in all).

A schematic for these measurements is shown in Figure 4.1.1. The instrument used

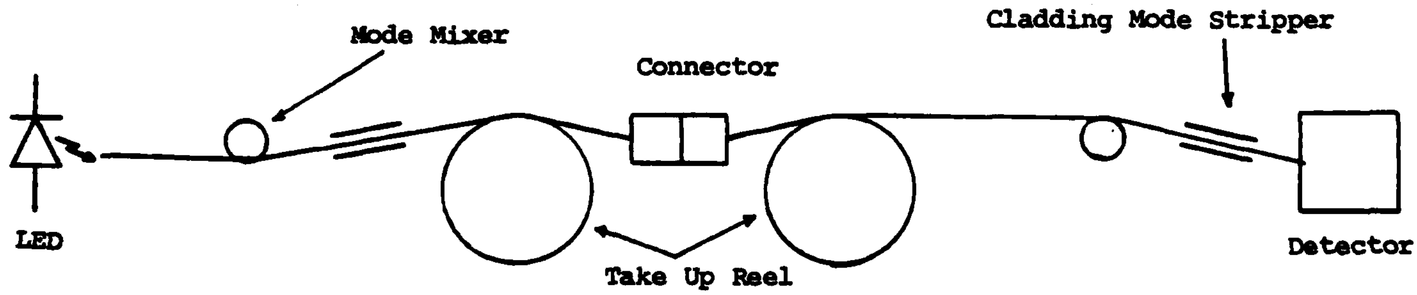

Figure 4.1.1 Measurement Configuration

to measure the transmission was a Photodyne Model 22XL optical multimeter. The meter power range covers the -90 dBm to +3 dBm range with an accuracy of $\pm$1%.

The results of these measurements are presented in Table 4.1.1. The table is laid out such that the reading of 3.2 dB in column 1A, row 2B is the loss for connector half 1, channel A (key side when looking at connector face on) transmitting to connector half 2, channel B (keyway). Combinations such as A-A or 1X-1Y are, of course, impossible. The average baseline loss was 3.2 dB (σ = 1.0 dB). This average includes readings for all possible combinations. It should be noted that channel 3A contains a lens damaged during the coating process. Disregarding combinations involving channel 3A the average would be 2.9 dB (σ=0.7). Crosstalk was below -60 dB in all cases.

REC \ TRANS.		1 A	1 B	2 A	2 B	3 A	3 B	4 A	4 B
1	A	------			3.3		2.8		3.0
	B			1.8		3.7		3.6	
2	A		1.8	------			4.0		3.5
	B	3.2				5.6		3.4	
3	A		2.8		5.3	------			3.6
	B	1.6		2.2				2.3	
4	A		3.0		2.8		3.4	------	
	B	3.0		3.4		4.5			

Table 4.1.1 Baseline Insertion Loss Results

The expected loss, assuming the allowed 0.1° misalignment between lens axes (section 3.3.1), is in the vicinity of 2.0 dB. The allocation of this loss is as follows: Fresnel reflections - 0.7 dB, angular offset - 0.7 dB[1], lens separation - 0.4 dB[2], spherical aberration - 0.2 dB[1]. The Fresnel reflection includes the loss from 6 interfaces in the transmission path (3 at 2%, 3 at 3%). The difference in the reflectivities stems from the fact that half of the coated interfaces are traversed in the reverse direction to that for which they were designed. These interfaces are: lens output face, window input face, and window output face (2 of each for 2 connector halves). The lens separation assumed is 0.120 inches.

4.2 ENVIRONMENTAL TESTS (PERFORMED BY AEL, LANSDALE, PA.)

The shock, vibration, and high temperature tests have been completed without incidence. The environmental parameters of each test are given below:

---

[1] Palais, Applied Optics, Vol. 19 (12), 15 June 80.

[2] IBID.

[3] Cline and Jander, Applied Optics, Vol. 21 (6), 1981.

TEST	METHOD[1]	CONDITIONS	CONFIGURATIONS
Shock	516.2(I)	Three shocks in each direction along 3 orthogonal axes. Pulse height - 40g's., pulse duration 11 msec.	Plug/Rec.
Vibration	514.2(VIII)	Sinusoidal vibration logarithmically sweeping the 5 Hz - 500 Hz - 5 Hz spectrum in 15 minutes. 3 hour cycling time in each of 3 axes. 4.2g maximum acceleration	Plug/Rec.
High Temp.	501.1 (I)	71°C, 48 hrs.	Plug/Plug, Plug/Rec., Plug/Rec.

The results of these tests are presented in Table 4.2.1 below. The losses were monitored continuously throughout the tests. The figures presented represent the maximum change induced by that particular environment. In the vibration test the X direction is along the plane containing the two lenses, Y lies along the connector axis and Z is orthogonal to them.

	CHANNEL 1	CHANNEL 2
SHOCK	0	0
VIBRATION		
X	0.3	0.2
Y	<0.1	<0.1
Z	0	<0.1
HIGH TEMP	3.3	0.2

Table 4.2.1 Change In Insertion Loss With Environment

[1] Applicable Method of MIL-STD-810

4.3 Discussion of Test Results

In as much as the environmental testing has just begun (12 tests remaining) in depth data analysis has not been performed. A few comments on the baseline measurements are nonetheless in order. The average reading, disregarding channel 3A, was 1.7 dB higher than the theoretical minimum (1.2 dB). Investigation into the possible causes of this led to the recognition that insufficient allowance had been made of the 15% disparity in focussed spot size between the tested 830 nm wavelength and the layer 633 nm HeNe laser radiation which was used in assembly. The potential offset thus allowed on assembly translates to a possible additional loss at 830 nm of $\sim$1 dB (section 2.0). Installation of higher precision micrometer movements on the assembly setup is anticipated to eliminate this problem. It is now expected that additional improvements in accuracy will have to be made in the existing fiber alignment slug assemblies.

Results of the remaining tests will be reported upon completion.

4.4 Environmental Test Equipment

The complete testing methodology, including data acquisition, is detailed in the connector Test Plan dated 24 May '82. However, some components have been changed and some added. These will be discussed here.

The low output impedance of the photodyne 22XL optometer has necessitated the use of a buffer amplifier between the analog outputs of the meter and the recording devices to be used. The buffers to be used have been constructed around the RCA CA3130 op amp as shown in Figure 4.4.1. The amplifier has been provided with a small gain to compliment the range of the strip recorder to be used. The gain of such a configuration is given by:

$$G = 1 + \frac{R_1}{R_2} = 1 + \frac{10K}{1K} = 11 .$$

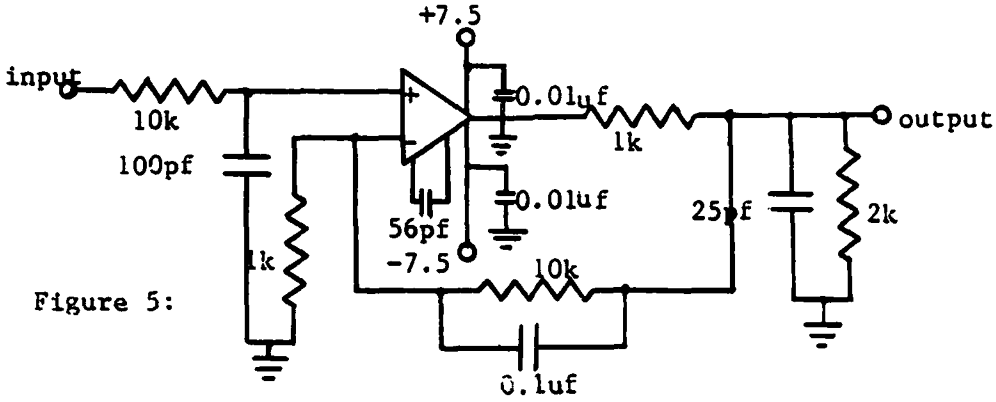

Figure 5:

Figure 4.4.1 Buffer Amplifier Schematic

TEST CHAMBERS AND APPARATUS

Shock	-	Shock Machine - AVCO - Model SM220
		Oscilloscope - Hewlett Packard - Model 141A
		Shock Amplifier - Endevco - Model 2740A
Vibration	-	Vibration System - Ling Electronics Model B335
		Vibration Control System - Hewlett Packard - Model 5427A
Salt Fog	-	Salt Spray Chamber - Industrial Filter & Pump - Model 411.1C
High Temp.	-	Temp/Hum./Alt. Chamber - Webber - Model WF27-100+350HV
Low Temp.	-	Temp. Chamber - Thermotron - Model F-42-CHV-25-25-CO_2
Temp. Shock	-	Temp./Hum./Alt. Chamber - Webber Model WF27-100 +350HV
		Temp. Chamber - Thermotron - Model F42-CHV-25-25-CO_2
Immersion	-	Immersion Tank - AEL
Humidity	-	Temp./Hum. Chamber - Blue M - Model FR-441F-MP
Dust	-	Sand & Dust Chamber - Plemco
		Dust Density Meter - Bethlehem Corp. Model 72-9-01
		Thermocouple Indicator - Dorie - Model 400A

Fiber Optic Expanded Beam Connector

1. Scope: These requirements cover the development of cable connectors (plugs) and bulkhead receptacles, utilizing an expanded beam device, for use in tactical fiber optic cable communication systems. The connector must be hermaphroditic and provide optical mating faces with minimal coupling loss between mating connectors. The design must be rugged to withstand tactical field applications.

2. Applicable Documents:

2.1 Issues of documents: The following documents of the issue in effect on date of invitation for bids or request for proposal form a part of these requirements to the extent specified herein.

Specifications

Standards

MIL-STD-1373	Screw-Thread, Modified 60° Stub, Double	8 Apr 71
MIL-STD-810C	Environmental Test Methods	10 Mar 75
DOD-STD-1678	Fiber Optic Test Methods and Instrumentation	30 Nov 77
MIL-STD-1188A	Packaging & Packing of Commercial Equipment	5 Jan 78

3. Requirements:

3.1 Objective: The objective of this program is to develop connectors for use with cables containing two low loss optical fibers. The fibers are graded index with attenuation under 6 dB/km at 850 nm. The connector design must utilize an expanded beam device for optical coupling between connectors, and be sufficiently versatile to have consistent optical performance with a variety of cable designs. The detailed characteristics and constructions of specified optical performance between mated connector pairs must be achieved by means of a suitable expanded beam technique.

3.2 Investigation: As a minimum, the following areas of investigation shall be pursued in the program:

3.2.1 Phasing: The program shall be conducted in two phases. The effort in Phase 1 shall be devoted to demonstrating the feasibility of the expanded beam device, in an actual quick coupling connector configuration, to meet the specified optical performance. In order to be considered feasible, it must be demonstrated that the optical performance is maintained throughout repeated mating cycles per paragraph 3.3.2.5. Phase 2 shall be devoted to achieving a rugged design which is resistant to the rough handling and wide range of environments typical of tactical field Army usage. The optical performance must be maintained throughout all mechanical and environmental tests herein specified.

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Attachment 2

3.2.2 Design Considerations

3.2.2.1 Plug: The major effort will be directed toward achieving a connector design which will provide a rugged, waterproof, environment-resistant termination for optical fiber cable. The approach for achieving the optimum connector design shall include, but not be limited to, the following considerations:

3.2.2.1.1 Field Repair: The objective is a connector design which is capable of assembly to the cable by trained technicians in a depot or mobile repair van. Designs which do not require the use of molding or potting techniques (repairable)* for accomplishing the assembly, as well as those which do (non-repairable)*, shall be investigated. The investigation will provide the basis for a decision as to which design will be selected for the final models. Accordingly, such factors as comparative costs, complexity, reliability, ease of assembly, and performance consistent with the technical evaluation criteria of paragraph 3.3 herein must be considered.

3.2.2.1.2 Cable Preparation: Methods and techniques for preparation of the cable ends for proper assembly with the connector shall be established. This shall include details as to tools, processes, solvents, and stripping dimensions for removal of jacketing, encapsulants, and fiber buffers and coatings. Preparation of optical fiber ends to provide the most efficient optical surface shall also be addressed.

3.2.2.1.3 Cable Strain Relief: The connector design shall include a suitable cable strain relief. The optical fibers which are contained within the confines of the connector housing must be isolated from direct tensile and bending forces which are applied to the cable extending beyond the confines of the connector. Furthermore, the strain relief must also provide resistance to cable pullout or damage when subjected to the cable retention, flex-life, and twisting tests of paragraphs 3.3.2.11, 3.3.2.12, and 3.3.2.13 herein. Materials used for potting or molding must be compatible with optical performance throughout the mechanical and environmental tests herein specified.

3.2.2.1.4 Fiber/Expanded Beam Device Interface: Particular effort must be devoted to the various factors involved with the interface between the optical fiber and the expanded beam device. These factors include, but are not limited to the following:

a. Positioning of the optical fiber for optimum optical performance shall not be dependent upon the skill of the technician making the assembly. Dimensions and design features, which are critical for optimum optical performance, shall be achieved in the connector piece-part fabrication process. This process must be conducive to volume production techniques.

b. The materials and design of the expanded beam device must be compatible with the materials used in conjunction with the buffered fibers. These include the fiber itself, the buffer, the protective coating(s) between the fiber and the buffer, the solvents used to remove protective coatings and buffers, and adhesives used to secure the fiber. Compatibility is to be determined by an analysis of the effect on optical performance throughout the environmental range specified herein.

* These terms are used for identification and convenience in discussion and in written material.

3.2.2.1.5 Mating Characteristics: The mating faces of the connector shall be optical with minimal crosstalk between adjacent optical paths and coupling loss between connectors. The optical mating faces must be suitably protected to prevent permanent degradation of light transfer between mating connectors as a result of repeated matings and unmatings, and exposure to moisture, water immersion, dirt, dust, sand, salt spray, and temperature extremes. The mating surfaces shall be easily accessible for cleaning with water, dry cloth, or small brush. The connector mating face and positive locking-coupling device shall be completely hermaphroditic to permit termination of both ends of the cable with identical connectors. The coupling device shall be free turning with respect to the connector shell.

3.2.2.2 Bulkhead Receptacle: The bulkhead receptacle shall include, but not be limited to, the following considerations:

3.2.2.2.1 Mating Characteristics: The mating characteristics shall be essentially the same as cited for the plugs in paragraph 3.2.2.1.5 herein. However, the device for coupling to plugs shall not be free turning with respect to the connector shell.

3.2.2.2.2 Mounting: The receptacle shall have a bulkhead, D-hole type mounting with jam-nut threads and panel seal. Provision shall be made for accommodating panels up to ¼ inch thick.

3.2.2.2.3 Termination: The receptacle shall be terminated with a short length (pigtail) of optical fiber attached to each expanded beam device. The fiber shall be the same as used in the cable. The purpose of the pigtail is for purposes of splicing to pigtails on sources, possible direct coupling to detectors, or direct splicing to cables. The length of pigtail shall be the minimum required to accomplish a good splice (splice loss less than 0.3 dB). Provision must be made for physical protection of the fiber pigtails (such as a removable protective cover) prior to installation in the equipment in which it is to be used.

3.3 Test & Evaluation:

The following criteria shall be used as a guide for evaluating the performance and establishing the optimum characteristics and performance requirements of the connectors. The evaluation need not be limited to the tests specified herein. Unless otherwise specified, the test specimen shall consist of a connector assembled to a cable. The length of cable shall be the minimum length required for valid measurement of the optical properties (paragraph 3.3.1) and to enable analysis of the effects of the mechanical and environment tests (paragraph 3.3.2) on the optical properties. The attenuation at 850 nm of individual fibers of the cables shall be no greater than 6.0 dB/km. Detailed test methods including the cable lengths, optical test measurements, and number of test specimens shall be provided for approval prior to the start of the technical evaluation.

3.3.1 Optical Tests:

3.3.1.1 Coupling Loss:

3.3.1.1.1 Plugs: The coupling loss of mated pairs of plugs, each assembled to a length of cable, shall not exceed 2.0 dB on an individual optical channel to channel basis.

3.3.1.1.2 Bulkhead Receptacles: The coupling loss of a mated pair of connectors consisting of a plug assembled to a length of cable and a bulkhead receptacle with optical fiber pigtails (as described in 3.2.2.2.3) shall not exceed 2.0 dB on an individual optical channel to channel basis.

3.3.1.2 Optical Crosstalk: Near-end and far-end crosstalk in adjacent optical channels of a mated pair of connectors, prepared as specified in 3.3.1.1.1 and 3.3.1.1.2 herein, shall be a minimum of 60 dB down from the signal level inserted in the exciting channel.

3.3.2 Mechanical and Environmental Tests: These tests are to be conducted after completing the Optical Tests of paragraph 3.3.1 specified herein. After each of these tests (or test groups), the test specimen is to be inspected under 5X magnification for physical deterioration as indicated for each test, and the Optical Tests of paragraph 3.3.1. The objectives are no degradation of the physical and optical properties of the test specimen.

3.3.2.1 Rotation: (Plugs) - The torque, measured with a torque wrench, required to rotate the coupling nut shall not exceed 0.75 inch-pound.

3.3.2.2 Shock Drop: Plug specimens shall be dropped at random six times mated from a height of ten (10) feet onto a 2-inch thick fir wood slab backed by concrete. The connectors shall be visually examined and the mated connectors tightened after each drop. The connectors shall have no loose parts, shall be capable of mating, and shall meet the requirements of paragraphs 3.3.1.1 and 3.3.2.1.

3.3.2.3 Shock: The test specimens shall be prepared in accordance with paragraph 3.3.1.1.2 herein. The bulkhead receptacle shall be mounted by its normal mounting hardware to the ¼ inch thick panel. Testing shall be in accordance with the Shock Test of MIL-STD-810, Method 516.2, Procedure I. A coupling loss of 2.0dB through the mated plug and receptacle shall be maintained throughout the test with no loosening of the coupling device, no damage and/or loosening of parts and the connectors shall be mechanically operable after the test is completed.

3.3.2.4 Vibration: The test specimen preparation, mounting and monitoring shall be as specified in paragraph 3.3.2.3 herein. Testing shall be in accordance with MIL-STD 810, Method 514.2, Procedure VIII. The evaluation criteria shall also be as specified in paragraph 3.3.2.3.

3.3.2.5 Mating Durability: Plug specimens shall be subjected to 1000 complete cycles of mating and unmating. One cycle shall consist of complete engagement and disengagement of connectors. Lubrication of coupling devices is not permitted. Coupling loss shall be monitored throughout the cycling. At the completion of the 1000 cycles, the connector mating surfaces may be cleaned as indicated in paragraph 3.2.2.1.5 herein. There shall be no evidence of mechanical damage, and the specimens shall meet the requirements of paragraph 3.3.1 and 3.3.2.1.

3.3.2.6 <u>Salt Fog</u>: Unmated plug and receptacle specimens shall be subjected to the Salt Fog Test of MIL-STD-810, Method 509.1. The connectors shall snow no evidence of corrosion, shall be capable of mating, and shall meet the requirements of paragraphs 3.3.1 and 3.3.2.1 herein.

3.3.2.7 <u>High Temperature</u>: Plug and bulkhead receptacle specimens shall be subjected to the High Temperature test of MIL-STD-810, Method 501.1, Procedure I, except that Step 4 shall be omitted. Mated specimens, prepared in accordance with paragraphs 3.3.1.1.1 and 3.3.1.1.2 herein, shall be montored for coupling loss throughout cycling. Unmated specimens shall also be subjected to the cycling. The connectors shall be capable of mating and shall meet the requirements of paragraphs 3.3.1.1 during and 3.3.2.1 after cycling.

3.3.2.8 <u>Low Temperature</u>: Plug and bulkhead receptacle specimens shall be subjected to the Low Temperature test of MIL-STD-810, Method 502.1, except that Step 4 shall be omitted. Mated specimens prepared in accordance with paragraphs 3.3.1.1.1 and 3.3.1.1.2 herein, shall be monitored for coupling loss throughout cycling. Unmated specimens shall also be subjected to the test. The connector shall be capable of mating and shall meet the requirements of paragraphs 3.3.1.1 during and 3.3.2.1 after coupling.

3.3.2.9 <u>Temperature Shock</u>: Plug and bulkhead receptacle specimens shall be subjected to the Temperature Shock Test of MIL-STD-810, Method 503.1. Mated specimens prepared in accordance with paragraphs 3.3.1.1.1 and 3.3.1.1.2 herein shall be monitored for coupling loss throughout the cycling. Unmated specimens shall also be subjected to the test. The connectors shall be capable of mating and shall meet the requirements of paragraphs 3.3.1.1 during and 3.3.2.1 after cycling.

3.3.2.10 <u>Immersion</u>: Mated and unmated plug specimens shall be immersed in a tank of water to a depth sufficient to cover the cable entry end, and subjected to a pressure equivalent to a 6-foot head of water for 24 hours. Coupling loss shall be monitored on the mated specimens throughout the test. There shall be no evidence of air bubbles throughout the test, and the mated specimens shall meet the requirements of paragraphs 3.3.1.1. The mating surfaces of the unmated specimens shall be dried thoroughly and then be capable of meeting the requirements of paragraph 3.3.1 herein.

3.3.2.11 <u>Humidity</u>: Plug and bulkhead receptacle specimens shall be subjected to the Moisture Resistance test of MIL-STD-810, Method 507.1. Preparation of specimens and coupling loss monitoring shall be as specified in paragraph 3.3.2.7 herein. The mated specimens shall meet the requirements of paragraph 3.3.1. The mating surfaces of the unmated specimens shall be dried thoroughly and then be capable of meeting the requirements of paragraph 3.3.1.

3.3.2.12 <u>Dust (Fine Sand)</u>: Plug and bulkhead receptacle specimens shall be subjected, unmated, to the Dust (Fine Sand) test of MIL-STD-810, Method 510.1, except that the air velocity shall be 100 to 500 feet per minute. There shall be no physical impairment of the specimens and they shall meet the requirements of paragraphs 3.3.1 and 3.3.2.1 herein.

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3.3.2.13 Cable Retention: The plug specimens shall be subjected to a static tensile load of 400 pounds for one minute applied to the cable at least 6 inches behind the back end of the plug. The load shall be applied in such a manner as to prevent cable damage in the vicinity of application of the load. Coupling loss shall be monitored during the loading period. The specimens shall suffer no physical damage and shall meet the requirements of paragraphs 3.3.1.1 and 3.3.2.1 herein.

3.3.2.14 Flex Life: The plug specimens shall be subjected to the number of continuous flex cycles specified in paragraphs 3.3.2.14.1 and 3.3.2.14.2. The connector shall be fastened securely and the cable held taut in the neutral axis. One complete flex cycle shall be $\pm$ 90° flex of the cable about the neutral axis. Coupling loss shall be monitored throughout the test. The specimen shall suffer no damage and meet the requirements of paragraph 3.3.1.1.

3.3.2.14.1 Room Temperature: The plug specimens shall be flexed for 2000 cycles at a temperature of 23° $\pm$ 1°C. Flexing shall be in two planes, each mutually perpendicular to each other and to the face of the connector. The line of intersection of the two planes shall pass through the center of the connector. Half the number of flexes shall be in one plane and half in the other plane.

3.3.2.14.2 Low Temperature: The plug specimens shall first be aged in a circulating air oven for a minimum of 48 hours at 85°C $\pm$ 2°C. The specimens shall then be conditioned for a minimum of 48 hours at -55 $\pm$ 3°C while attached to the flex life tester. Flexing shall then be conducted as specified in 3.3.2.14.1 except that the total number of flex cycles shall be 1000 (500 in each plane).

3.3.2.15 Twist: Mated plug specimens shall be tested, holding the connectors stationary, and gripping the cable of one specimen six (6) inches behind its connector in such a manner as not to be damaging to the cable. The cable shall then be subjected to 1000 twist cycles. One cycle shall consist of a 180° twist ($\pm$ 90° about the neutral axis). Coupling loss shall be monitored throughout the cycling. There shall be no physical damage to the specimens and they shall meet the requirements of 3.3.1.1.

3.3.2.16 Mud Test: Soak the uncapped connector halves of a connector pair in a mud bath for 5 minutes, followed by a cleaning. Mate the connectors and measure the insertion loss. The insertion loss should not be increased by mud exposure. Repeat the above test ten times.

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TABLE I. CABLED FIBER CHARACTERISTICS

	VALTEC	TIMES	ITT	GALILEO	BIW
Attenuation @ 850 nm	$\leq$ 6 dB/Km	$\leq$ 6 dB/Km	$\leq$ 6 dB/Km	$\leq$ 7 dB/Km (at 900nm)	$\leq$ 6 dB/Km
Dispersion @ 850 nm	$\leq$ 1ns/km	$\leq$ 1ns/km	$\leq$ 2ns/km	$\leq$ 2ns/km	$\leq$ 2ns/km
Fiber Core Diameter	50 μm	50 μm	50 μm	50 μm	50 μm
Fiber Cladding OD	125 μm	125 μm	125 μm	125 μm	125 μm
Fiber Jacket Diameter	.7 mm	550 μm	.94 mm	.020"	.058"
Numerical Aperture	$.2 \pm .02$	0.16	.17 - .19	.21	.2
Tensile Strength (Proof Test)	100 kpsi	25 kpsi	100 kpsi	50 kpsi	25 kpsi

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